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Relative measure of bulk density to characterize compaction of forest soils caused by harvest

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Abstract

This study evaluated usefulness of comparing field soil bulk density to the theoretical maximum bulk density determined with the Proctor compaction test. Total of 93 soil samples for determination of the maximum (Proctor) compaction value were collected from the existing long-term soil productivity (LTSP) sites and several other long-term sites in British Columbia. The long-term sites were included into this study based on the availability of a complete record of soil bulk density and tree growth data. The maximum value, along with previously determined field bulk density were used to determine a "relative" soil bulk density. Soil texture and total carbon were also determined on the samples collected. We found that field sampling and evaluation of MBD was suitable for field investigations and could contribute valuable information to research projects at a modest cost. A strong relationship exists between MBD and θ_{MBD}. Maximum bulk density was strongly influenced by total carbon content and this relationship needs to be further evaluated. Our early efforts to determine RBD by matching field bulk density data with Proctor compaction data appeared to provide reliable RBD values in many cases, but further evaluation will be needed to obtain reliable RBD for several sites. Based on our early calculations and interpretations, we believe the method has promise, but reliable results for highly variable sites may require a higher intensity of sampling than we used (usually four per site).

Key words: Forest soil, soil compaction indices, Proctor bulk density

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1. Introduction

Healthy soils are an essential part of healthy and productive forest ecosystems, but soil productivity is often impaired as a result of compaction caused by machine traffic. To ensure that soil productivity is maintained during harvesting and other forest operations, reliable methods are needed to evaluate soil conditions and determine which conditions are conducive to tree growth. One of the most cost-effective methods of assessing soil compaction involves determination of the bulk density, while some recent studies evaluated the use of penetrometer as a mean of soil compaction assessment (Krzic et al. 1999, Krzic et al. 2001, Bulmer et al. 2002).

In studies of soil compaction, measured bulk density on disturbed sites is compared to values for undisturbed sites to determine if compaction has occurred. The extent of compaction varies depending on the type of machine traffic, the number of passes, and soil conditions (texture, organic matter and water contents) at the time of disturbance. A question that is commonly asked is 'at what level of soil compaction will tree growth be impaired?' Finding the answer to this question is difficult, because tree growth is affected by a range of interacting site and soil growth-limiting factors such as soil moisture regime and climate, soil physical conditions, and nutrient status. Even where many of these factors are held constant, tree growth and soil bulk density may only be weakly correlated because either (i) threshold values of soil bulk density have not been exceeded, and/or (ii) other growth limiting factors have greater effect on tree growth.

Soil bulk density is strongly influenced by soil texture and organic matter content, as well as machine traffic. Considerable variation in bulk density determinations can obscure trends. Evaluating the relative bulk density may eliminate the need for determination of an unique growth-limiting threshold for soils with different contents of organic matter and texture.

The **objectives** of our project are to:

1. determine maximum (Proctor) bulk density for soils from the long-term soil productivity (LTSP) sites in BC,
2. determine relative bulk density for soils from the LTSP sites,
3. evaluate the relationships between tree growth, field (actual) soil bulk density, and relative soil bulk density.

Maximum bulk density (MBD) evaluated by the Proctor analysis has been defined as the highest compactibility value for a particular soil (Stengel, 1984). It is determined by locating the peak on the Proctor compaction curve (dry bulk density versus gravimetric water content).

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2. Project Details

2.1. Site Description

The study was carried out on the existing Long-Term Soil Productivity sites (LTSP) in BC, long-term skid trail studies in the Kootenays, and root removal trials in the southern Interior. Currently there are 62 LTSP sites throughout North America that were initiated as a collaborative research effort carried out by the US Department of Agriculture, US Forest Services, Canadian Forest Service, BC Ministry of Forests, and various universities and industry groups in North America. The general objective of this cooperative study is to determine interactions of soil organic matter removal and compaction caused by forest harvesting on soil productivity in major forest types.

The LTSP sites that are located in the following Forest Districts in BC are included in our study:

a) Dawson Creek (Kiskatinaw): BWBS biogeoclimatic zone

b) Prince George (Log Lake)/ Lakes (Topley, Smithers) / Williams Lake (Skulow Lake): SBS biogeoclimatic zone

c) Kamloops: IDF biogeoclimatic zone

d) Invermere: IDF biogeoclimatic zone – calcareous soil

The long-term skid trail studies in the Kootenays are maintained by the Canadian Forest Service, while the root removal trials in the southern Interior are carried out by the BC Ministry of Forests and Canadian Forest Service.

A total of 93 samples were analysed from 16 sites and list of the site codes used in the study, as well as how many samples were taken at each site and at what depth are given in Table 1.

Table 1. Site description, depth of sampling and number of samples taken per site

Sample Code	Sample Description	From	No. Plots	Depths (m)	Samples/site
BP	Black Pines LTSP*	Kamloops	4	0-0.2	4
DA	Dairy LTSP	Kamloops	4	0-0.2	4
DW	Boreal (Kiskatinaw) LTSP	Dawson Creek	6	0-0.1 & 0.1-0.2	12
EM	Emily LTSP	Invermere	2	0-0.1 & 0.1-0.2	4
KO	Kootenay East LTSP	Invermere	4	0-0.1 & 0.1-0.2	8
LL	Log Lake LTSP	Prince George	4	0-0.2	4
MP	McPhee LTSP	Invermere	4	0-0.1 & 0.1-0.2	8
MU	Mud Creek LTSP	Invermere	4	0-0.1 & 0.1-0.2	8
OC	O'Connor LTSP	Kamloops	4	0-0.2	4
RO	Rover LTSP	Invermere	3	0-0.1 & 0.1-0.2	6
SK	Skulow LTSP	Prince George	3	0-0.2	3
TO	Topley LTSP	Smithers	4	0-0.2	4
GT	Gates Creek Stumping Trial	Vernon	2	0-0.1 & 0.1-0.2	4
MI	Miriam Creek Rehabilitation Trial	Vernon	6	0-0.2	6
PH	Phoenix Canadian Forest Service Stumping Trial	Vernon	2	0-0.1 & 0.1-0.2	4
VV	Vama Vama Rehabilitation Study	Prince George	6	0-0.1 & 0.1-0.2	10

2.2. Materials and Methods

2.2.1. Maximum Bulk Density

From September to November 2002 soil samples were collected from the sites listed in Table 1 for determination of maximum bulk density. About 30-40 kg of soil was collected from each treatment, packed in a plastic tubs, and sent to the soil laboratory at the University of British Columbia.

The maximum bulk density was determined using the Proctor test (ASTM D698-00a, method A). The soil was first passed through a 19-mm sieve followed by sieving though a 4.75-mm sieve. Water was added to a subsample (2.3 kg) of the sieved soil until it neared the anticipated moisture at MBD. The water content at MBD (θ_{mbd}) is typically slightly less than the plastic limit and was initially estimated by hand test. Once θ_{mbd} was determined four more subsamples were prepared, two below and two above this value. The five moistened samples were then left to equilibrate overnight. The soil was compacted in a standard (9.43×10^{-4} m^3) mold using a 2.5 kg rammer falling freely from a height of 0.3 m. The soil was added to the mold in three layers and 25 blows of rammer were applied to each layer. Total compactive effort applied to the sample was 600KN-m/m^3.

Excess soil was removed from the top of the mold and the compacted sample was weighed. Gravimetric water content (θ) was determined for each sample by placing it in a drying oven at 105°C for 16 hours. Bulk density (kg/m^3) was then determined as follows:

$$Wet\ Bulk\ Density\ (WBD) = \frac{wet\ soil\ (kg)}{volume\ of\ mold\ (m^3)} \qquad (1)$$

$$Dry\ \ Bulk\ \ Density\ \ (DBD) = \frac{WBD\ \ (kg\ \ m^{-3})}{1-\theta} \qquad (2)$$

Values were plotted on a graph of dry bulk density (DBD) vs. θ and the points fitted with a best fit curve (third order polynomial). From the resulting compaction curve the Proctor BD was determined from either a) the peak or b) the highest sample value where the peak of the curve lay below. Approximately 500 g from each sample was sieved through a 2-mm sieve to determine the percentage fine fraction. Proctor BD was then corrected to fine fraction MBD as follows:

$$MBD\,(kg\,m^{-3}) = \frac{FF\,(kg) \times \mathrm{Pr}\,octor\ BD\,(kg\,m^{-3})}{1-\left(\dfrac{CF\,(kg) \times \mathrm{Pr}\,octor\ BD\,(kg\,m^{-3})}{2650\,kg\,m^{-3}}\right)} \qquad (3)$$

2.2.2. Plasticity and Consistency

Following compaction, three hand tests were performed on each of the five subsamples to determine plasticity and consistency. In the moisture test, a small amount of soil is squeezed by hand. The amount of moisture left behind on the hand is recorded as a percentage of the total surface area that the soil came in contact with. The exposed hand surface may be recorded as 0, >25, 25, 50, 75, 100 or >100% moist. In the clod test, a small amount of soil is again squeezed by hand. If a soil does not form a clod, it is recorded as "no clod". If a clod is formed, it is then tapped four times with a single finger. The amount of clod that breaks apart under this pressure is recorded as 25, 50 75 or 100%. In the worm test, the sample is rolled between two hands into a worm. If a worm cannot be formed "no worm" is recorded and if only a rough shape is possible "rough" is recorded. If a worm can be rolled the length and width of the worm are recorded. These hand tests may be used in the field by foresters wishing to determine if harvesting at a particular range of θ_m could severely increase compaction levels of a site.

2.2.3. Relative Bulk Density

Field soil bulk density (fine fraction), total carbon and tree growth data, which had been collected in previous field studies, were obtained from researchers responsible for the field studies. The relative bulk density (RBD) is calculated as follows:

$$RBD\ (\%) = \frac{Field\ BD}{MBD} \times 100 \qquad (4)$$

In order to calculate an accurate RBD value for a particular site, characteristics such as texture, carbon content, and mineralogy need to be the same for the field bulk density sample and the sample used to determine MBD with the Proctor test. Since these soil are often highly variable on forest soils, matching the field bulk density samples with the appropriate MBD can be challenging. For the purposes of this preliminary study, this was done primarily by matching carbon (field and Proctor) as closely as possible. Where this was not possible (either because the field carbon values were not available, or because no similar Proctor sample had been collected), the matching was done based on geography. Further refinement of the important process of matching of samples is planned, and will include an evaluation of soil texture, and a site-by-site review of our data by researchers familiar with the field sites, so that particular characteristics of the study sites are incorporated into the decision.

2.2.4. Texture and Total Carbon

Soil texture was determined for each sample by the hydrometer method (Gee and Or 2002). Preparation for texture analysis required eliminating organic matter through the addition of hydrogen peroxide and heat. For carbonate rich samples from the Invermere area, a sodium acetate buffer was added to breakdown the carbonate particles before conducting texture analysis (Gee and Or 2002).

Total soil C was determined by a dry combustion method (Nelson and Sommers, 1982) using a LECO analyzer.

2.2.5. Tree Growth

We investigated the relationship of RBD and growth for the following sites: BP, DA, DW, LL, MI, OC, SK, TO, VV (see Table 1 for site codes). To investigate the relationship between RBD and tree growth, RBD was plotted against total height and height increment for each site. Site data were not pooled since growth measurements varied from 1 year to 8 year height data and different tree species were planted at different sites. Correlation analysis was performed on scatterplots that showed a linear pattern, to quantify the strength of the relationship. For each site, average growth responses were calculated. Then average tree growth on a given plot was compared to the sites' average growth response. If the plot average was greater than the site's average, then a positive (+) effect was assigned and if the plot average was smaller than the site's average then we noted a negative (-) effect.

3. Results and Discussion

3.1. Maximum Bulk Density

The compaction curves (dry bulk density vs. water content) for all 93 samples, sorted by site are given in Appendix A. Texture and classification, total carbon, MBD and θ_{mbd} of each sample are listed in Tables 2 and 3 in Appendix B.

The water content at which the soil becomes most compact under Proctor standard effort is referred to as the critical water content or maximum bulk density water content (θ_{mbd}). Maximum bulk density for each plot were plotted against θ_{mbd} (Figure 1.) An inverse linear plot describes the relationship very well ($y = 2.0932 + (-2.7167\theta_{mbd})$; $r^2 = 0.89$).

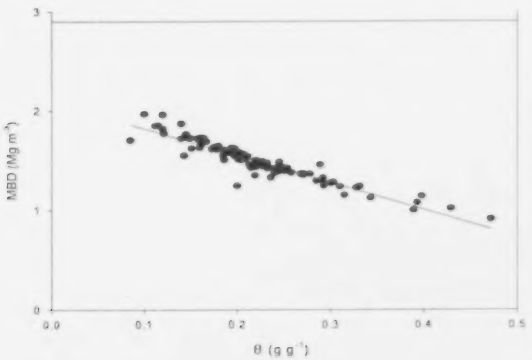

Figure 1. Relationship between soil water content at maximum bulk density and maximum bulk density of 93 samples collected at 16 sites in BC

When MBD_{FF} for all 93 samples from all 16 sites are plotted against percent total carbon (Figure 2) a significant relationship was observed ($r^2 = 0.68$). Separate analyses for sand content (Figure 3), silt and clay content (Figure 4, Appendix B) and depth (Figure 5, Appendix B) resulted in similar relationships (Table 4) between carbon and maximum bulk density, indicating that these measures of particle size distribution were not well correlated with MBD_{FF}.

Table 4: Simple regression equations between MBD and Total Carbon (TC)

	Equation	r^2
MBD vs. TC	MBD = 1.7423 + (-0.117TC)	0.68
MDC vs. TC <40% Sand	MBD = 1.7102 + (-0.1149TC)	0.67
MDC vs. TC >40% Sand	MBD = 1.7692 + (-0.1153TC)	0.69
MDC vs. TC <50% Silt and Clay	MBD = 1.7739 + (-0.1084TC)	0.67
MDC vs. TC 50-60% Silt and Clay	MBD = 1.7256 + (-0.1176TC)	0.65
MDC vs. TC <60% Silt and Clay	MBD = 1.7171 + (-0.112TC)	0.70
MBD vs. TC 0-10cm	MBD = 1.6884 + (-0.1061TC)	0.63
MBD vs. TC 10-20cm	MBD = 1.7326 + (-0.1201TC)	0.67

Weak or non-existent relationships between MBD_{FF} and sand, silt, or clay are also illustrated in Figures 6, 7, 8, 9 and 10 [MBD = 1.5231 + (-0.0022 Clay); r^2= 0.007], silt [MBD = 1.6148 + (-0.0027Silt); r^2= 0.032] or sand [MBD = 1.3953 + (0.0023Sand); r^2=0.036]. There is also no relationship when the data is sorted by depth or carbon content (Figures 9 and 10, Appendix B).

These results illustrate the important effect of organic matter on the MBD_{FF}. We are continuing to explore the significance of poor relationships between soil texture and MBD_{FF}, and the role of other factors that affect maximum bulk density of a particular soil. Such investigations are necessary considering that soil texture is often cited as a critical factor affecting the response of soil to machine traffic, tillage and other forms of disturbance.

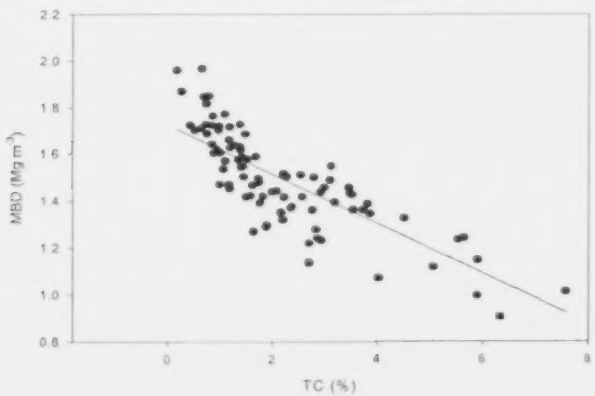

Figure 2: Relationship between total carbon and maximum bulk density of 91 samples collected at 16 sites in BC

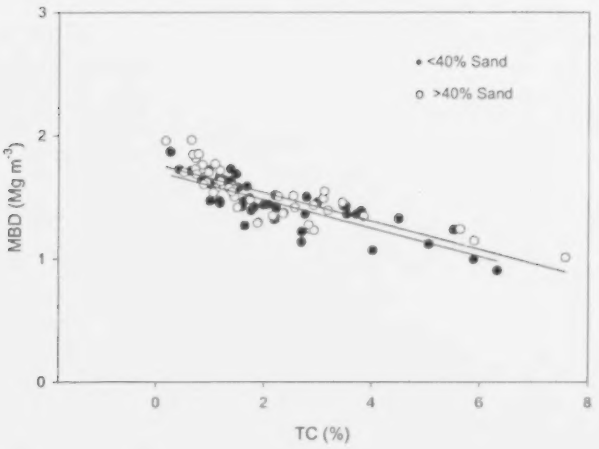

Figure 3. Relationship between total carbon sorted by sand content and maximum bulk density of 91 samples collected at 16 sites in BC

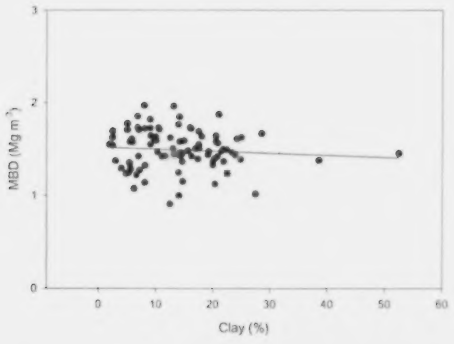

Figure 6: Relationship between percent clay content and maximum bulk density of 93 samples collected at 16 sites in BC

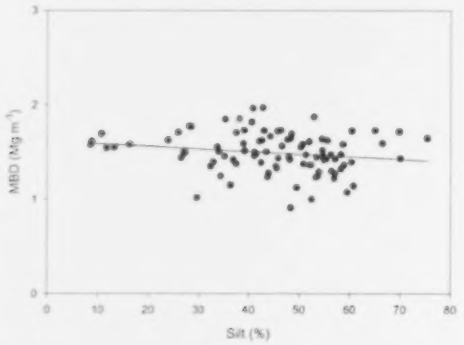

Figure 7 Relationship between percent silt content and maximum bulk density of 93 samples collected at 16 sites in BC

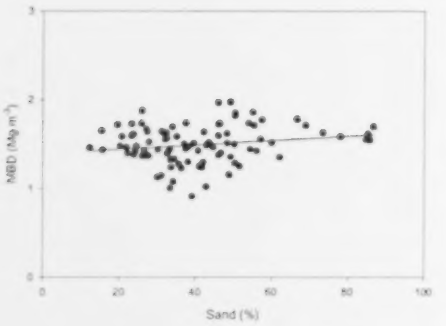

Figure 8 Relationship between percent sand content and maximum bulk density of 93 samples collected at 16 sites in BC

Maximum bulk density was greater at 10-20 cm depth than at 0-10 cm (Figure 11). Variation in MBD_{FF} across study sites was often high. For example, at Dairy Creek, near Kamloops, MBD_{FF} ranged from less than 1400 kg m^3 to more than 1800 kg m^3, and the variation appeared to be a result partly of variation in carbon content (Table 2). The sample with low MBD_{FF} also had the highest carbon content, while the sample with the highest MBD_{FF} had the lowest carbon content. These results illustrate the variability that is typical of many forest research sites, and illustrate the need to obtain an appropriate number of samples to collect to fully characterize site conditions.

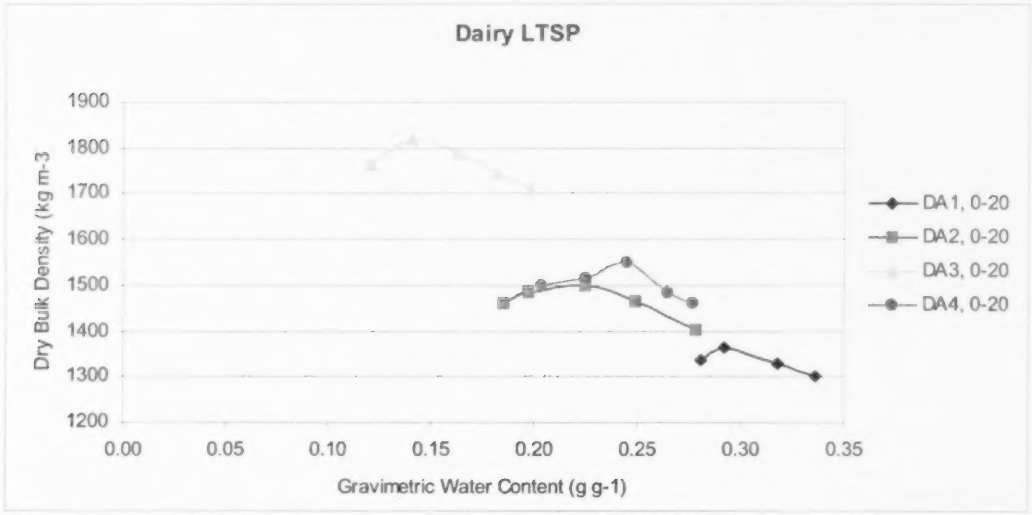

Figure 11. Relationships between the gravimetric water content and dry bulk density used for determination of the maximum soil bulk density at four locations within the LTSP site at Dairy Creek, near Kamloops.

Maximum bulk density was 0.12 Mg m^{-3} greater at 10- 20 cm depth than at the surface 0-10 cm depth.

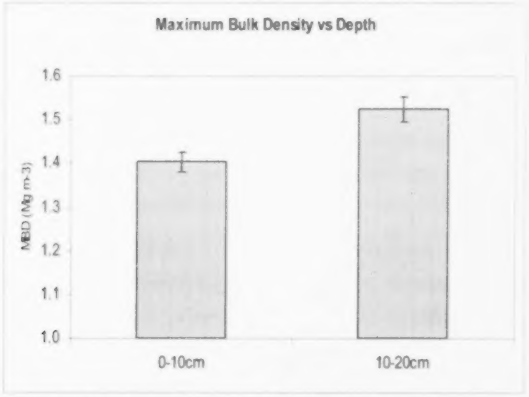

Figure 12. Maximum soil bulk density obtained in all 93 samples at 0-10 and 10-20 cm depths.

3.1.1. Hand Testing

The results of the hand tests are summarized in Table 5. For many of the soils, a moisture test showing 25-50 percent of the hand being wetted corresponds to soils that are at a moisture

content where they are highly susceptible to compaction. Also, at the optimum water content for compaction, clods formed will be mostly (75%) or entirely broken with gentle tapping. None of the soils formed a worm at the optimum soil moisture content for compaction. These results illustrate the potential applicability of simple field hand tests for determining the compaction susceptibility of soils. Further evaluation of the results for each subsample used for the Proctor test will be carried out to help to refine these interpretations.

Table 5. Average results of hand moisture test, clod test and worm test at MBD

Site	Textural Class	Average water content at Max Db ($g\ g^{-1}$)	Moisture test (%)	Clod test (%)	Worm test
BP	Silt Loam	0.21	25	75	no worm
DA	Silt Loam	0.22	25	75	no worm
DW	Silt Loam	0.22	25	50	no worm
EM	Sandy Loam	0.19	25	75	no worm
GT	Loam	0.26	25	50	no worm
KO	Silt Loam	0.24	25	50	no worm
LL	Loam	0.20	25	75	no worm
MI	Sandy Loam	0.14	25	75	no worm
MP	Silt Loam	0.32	50	50	no worm
MU	Silt Loam	0.21	25	75	no worm
OC	Silt Loam	0.20	50	75	no worm
PH	Silt Loam	0.34	50	50	no worm
RO	Loamy Sand	0.19	75	100	no worm
SK	Sandy Loam	0.15	50	100	no worm
TO	Sandy Loam	0.27	25	50	no worm
VV	Loam	0.18	25	100	no worm

Relative Bulk Density

From the 16 study sites, relative bulk density (RBD) has so far been calculated for nine sites, Dawson Creek (DW), Log Lakes (LL), Topley (TO), Skulow (SK), Black Pines (BP), Dairy (DA), O'Connor (OC), Vama Vama (VV) and Miriam Creek (MI). The field carbon, Proctor carbon and carbon difference (field carbon – Proctor carbon) is provided in Tables 6 – 14 in Appendix C for these nine sites.

No relationship was found between either RBD and total field carbon or total Proctor carbon (Figures 13 and 14). Field and Proctor carbon contents were used to match field and maximum (Proctor) bulk densities, and then used to calculate RBD.

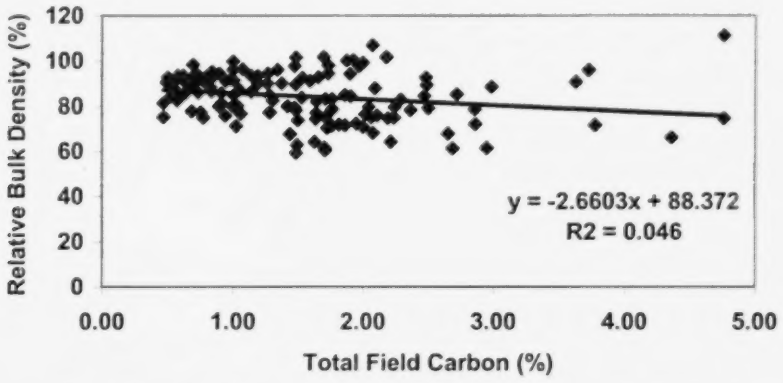

Figure 13. Relationship between total field carbon and relative bulk density of samples from selected nine sites in BC

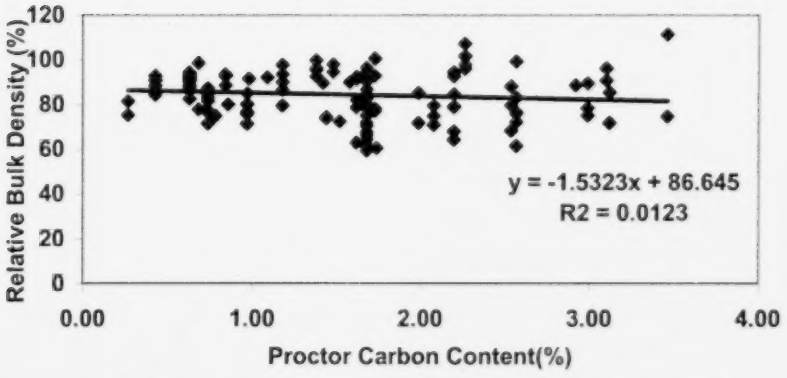

Figure 14. Relationship between total Proctor carbon and relative bulk density of samples collected at selected nine sites in BC

No relationship was found between either RBD and total field carbon or total Proctor carbon

(Figures 13 and 14). These results illustrate the potential of the relative bulk density concept to "normalize" bulk density values and reduce the variation caused by changes in organic matter content.

Figure 13 also shows the range of RBD values obtained by our preliminary calculations, where field bulk density samples and Proctor samples were matched based on similar C content, or geographic proximity. Values for RBD, using this preliminary method ranged from below 60% to over 100%. Several values compare to the expected range for well matched samples of 70 -- 90%. High values could indicate either (1) that the field bulk density sample had lower c content than the Proctor sample used to determine MBD_{FF}, or (2) that the machine traffic exerted a greater compactive effort than the Proctor test. We believe that the likelihood of (1) is greater than (2), but we will further evaluate the data. For samples with RBD Lower than 70 percent, a similar mismatch of samples may have occurred, with the field bulk density sample having a higher C content than that of the sample used to determine MBD_{FF}.

Carbon difference was calculated as the difference between field carbon and Proctor carbon content. This difference was calculated to assess the accuracy of matching sampling points between field bulk and Proctor bulk densities. If the carbon difference is >0.5% we considered that the data may not produce a reliable RBD value. All sites (Apendix C, Tables 6-14) show small carbon differences except for some of the Vama Vama (VV) treatment plots where six treatment plots out of 24 showed a carbon difference value greater than 0.5%.

Although no statistical analysis has been performed, organic matter removal and compaction treatments appeared to affect RBD on the LTSP plots. Within each compaction treatment, sites with OM3 treatments (removal of stems, coarse woody debris and forest floor) had the highest RBD (Fig. 15). Compaction treatments C1 (medium compaction) and C2 (high compaction) appeared to have higher RBD than C0 (no compaction). Considering that these results are pooled over several study sites with varying characteristics, these results serve to illustrate the potential for interpretations based on RBD. Undisturbed plots (OM1, C0) tended to have RBD values between 70 and 80%.

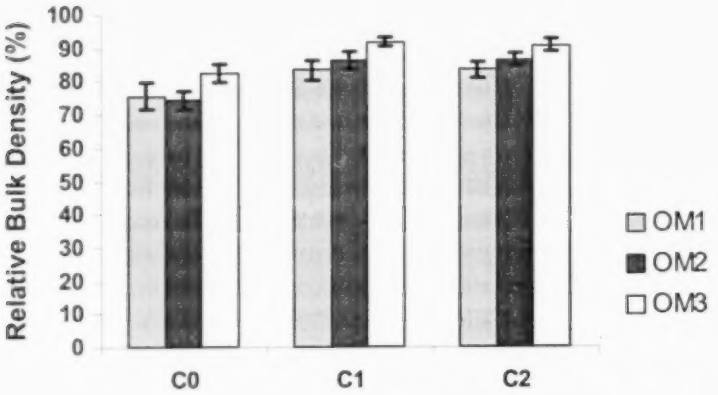

Figure 15. Relative bulk density with organic matter removal and compaction treatments for BP, DA, DW, LL, OC, SK, and TO LTSP sites (error bars represent 2 standard error).

3.1.2. Tree Growth

We did not find a relationship between RBD and tree growth on most sites (Appendix C), which could be attributed to a number of reasons, including (1) there were no growth differences between the study plots, (2) compaction was not a limiting factor on the site, (3) RBD as we have calculated it is not reflecting different compaction levels accurately, or (4) trees are too young to express differences. We are continuing to evaluate these concepts on a site-by site basis.

On one site (Dawson Creek), RBD at 0-10 cm depth was moderately well correlated with tree growth (Fig. 16). At this site poor tree growth is associated to high RBD values. Height increment (R^2 = 0.47, $p<0.01$) was somewhat better correlated to RBD than total height (Fig. 16).

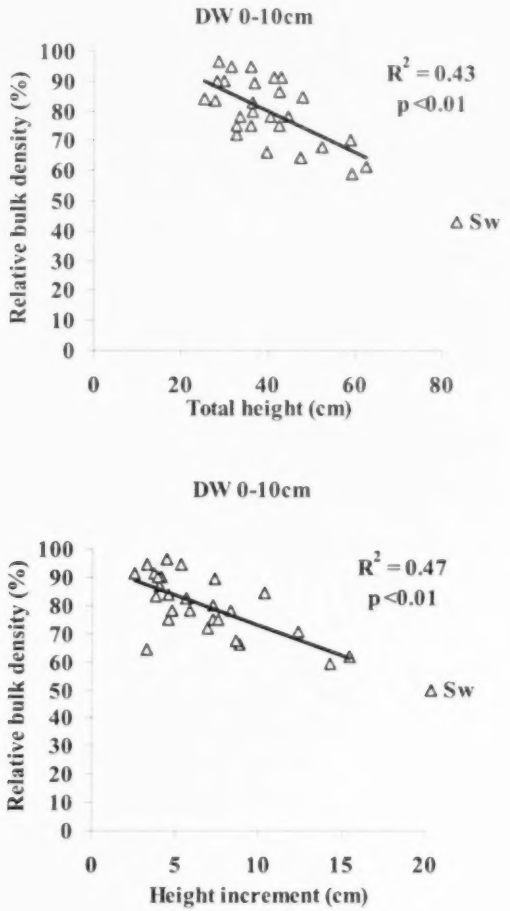

Figure 16. Relationships between total tree height and relative bulk density at 0-10 cm depth (upper graph) and height increment and relative bulk density at 0-10 cm depth (lower graph) at Dawson Creek (DW) site.

Across all plots RBD values between 50-74% were associated with few (8%) negative growth effects, while higher RBD values were often associated with negative or mixed growth response (Table 15).

Table 15. RBD and its effect (positive "+", negative "-") on tree height increment.

RBD (%)	No. of Samples	Relative growth effect + (%)	- (%)
50-74	12	92	8
75-84	31	35	65
>85	44	41	59

Sites used: DW (3 years), LL (5 years), MI (2 years), SK (5 years), TO (5 years). Only sites with height increment data.

4. Conclusions

1. We found that field sampling and evaluation of MBD was suitable for field investigations and could contribute valuable information to research projects at a modest cost.

2. A strong relationship exists between MBD and θ_{MBD}. Our results will contribute to a better understanding of the role of water content on compaction susceptibility, and will also help to calibrate hand tests that are applicable in field situations.

3. Maximum bulk density was strongly influenced by total carbon content and this relationship needs to be further evaluated. We expect it to provide a valuable confirmation for compaction assessment on BC' forest soils.

4. At the soil surface (0-10cm) MBD was slightly lower than at 10-20 cm depth, which likely reflects lower C content in the subsoil.

5. Our early efforts to determine RBD by matching field bulk density data with Proctor compaction data appeared to provide reliable RBD values in many cases, but further evaluation will be needed to obtain reliable RBD for several sites.

6. Relative bulk density appeared to be related to site treatments on the LTSP sites (pooled information).

7. Relative bulk density appeared to be related to tree growth on one LTSP site (i.e. Dawson Creek site).

8. Based on our early calculations and interpretations, we believe the method has promise, but reliable results for highly variable sites may require a higher intensity of sampling than we used (usually 4 per site).

5. Literature Cited

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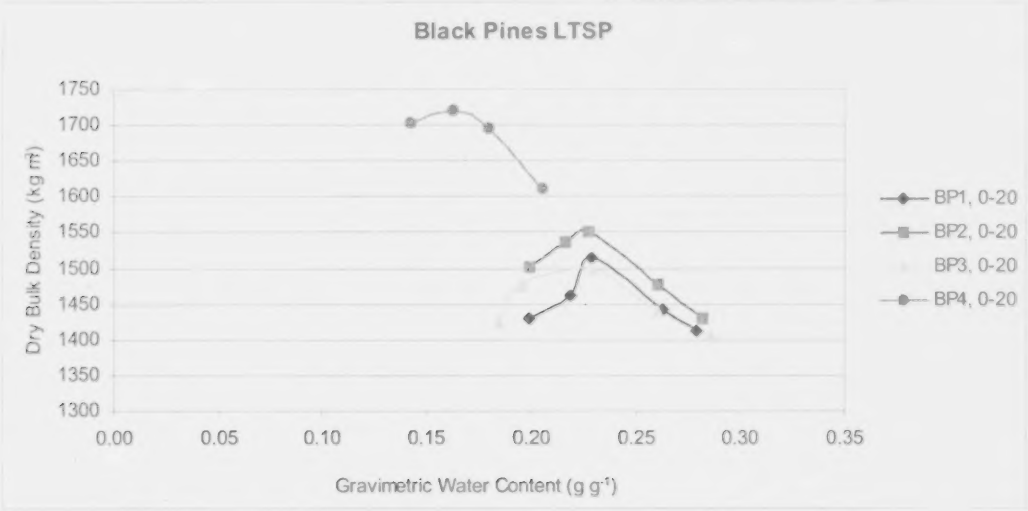
6. Appendices

Appendix A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1700
1650
1600
1550
1500
1450
1400
1350
1300
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0.05
0.10
0.15
0.20
0.25
0.30
0.35
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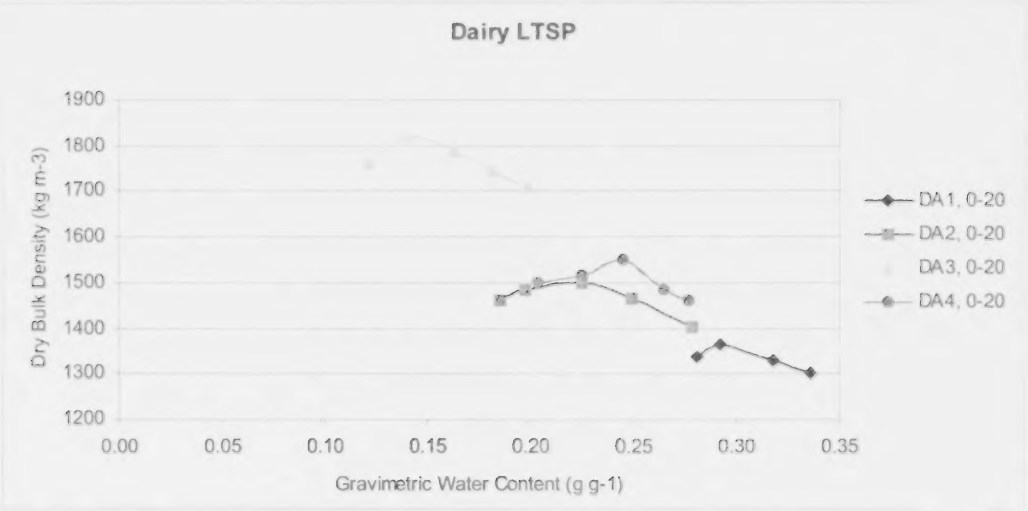
BP2, 0-20
BP3, 0-20
BP4, 0-20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0.15
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0.35
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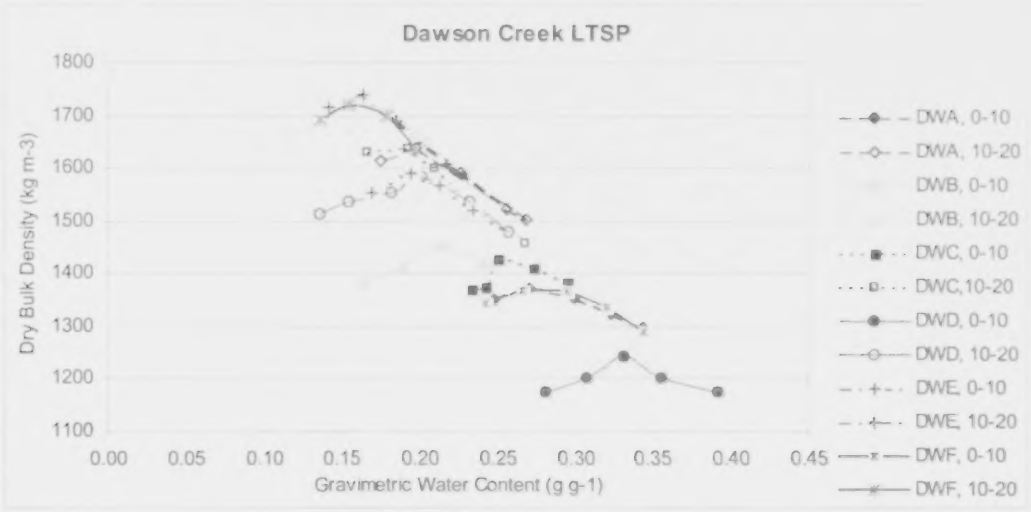
DA3, 0-20
DA4, 0-20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1100
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0.35
0.40
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DWB, 0-10
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DWC, 0-10
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DWD, 0-10
DWD, 10-20
DWE, 0-10
DWE, 10-20
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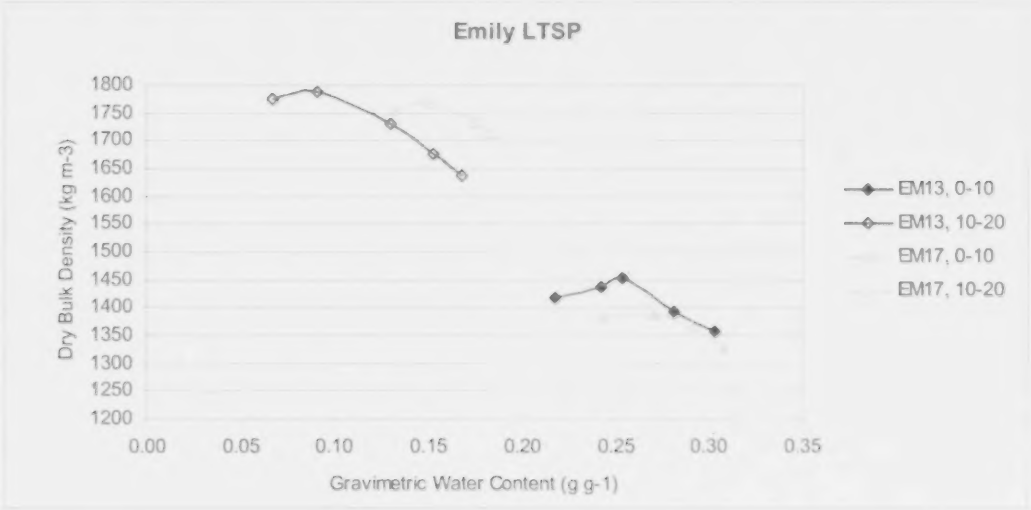
DWF, 10-20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1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
0.00
0.05
0.10
0.15
0.20
0.25
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0.35
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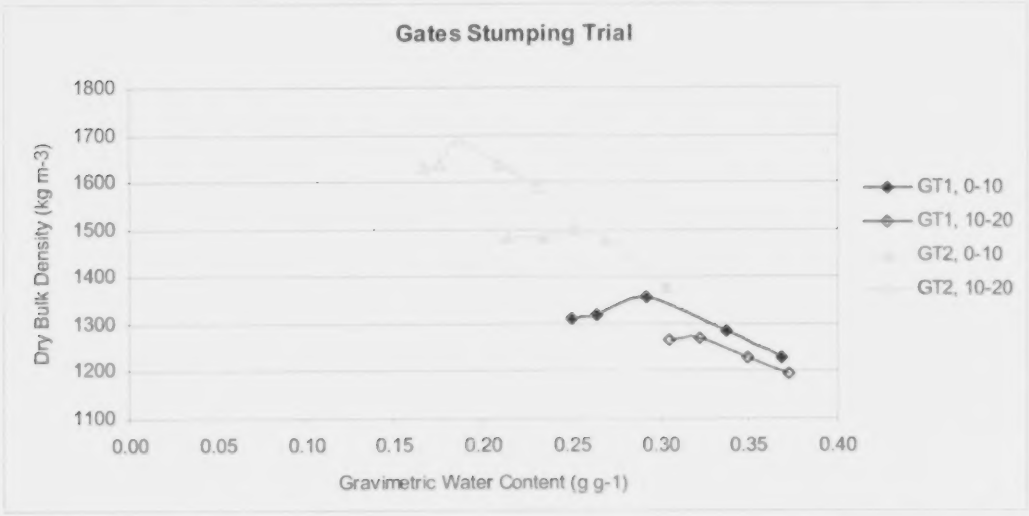
EM17, 0-10
EM17, 10-20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1200
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0.10
0.15
0.20
0.25
0.30
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0.40
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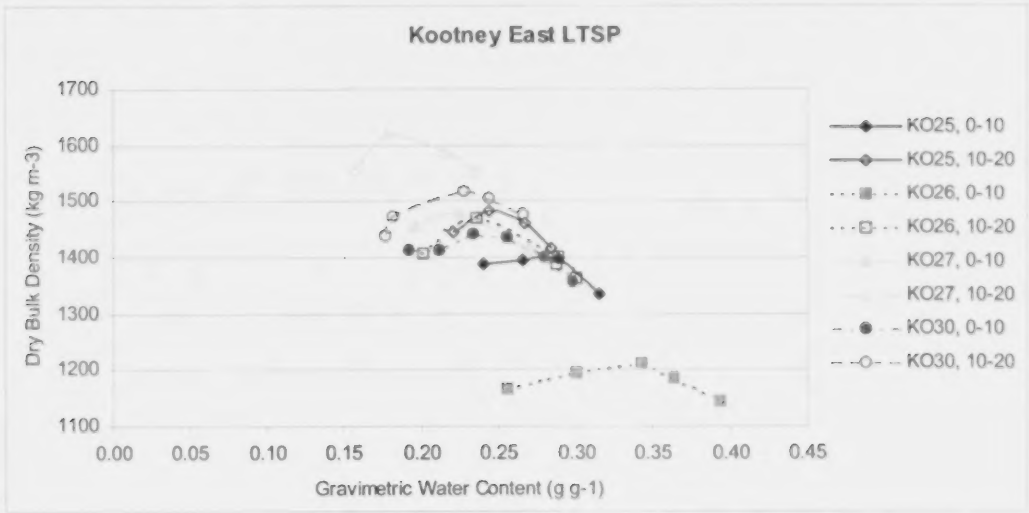
GT2, 0-10
GT2, 10-20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0.35
0.40
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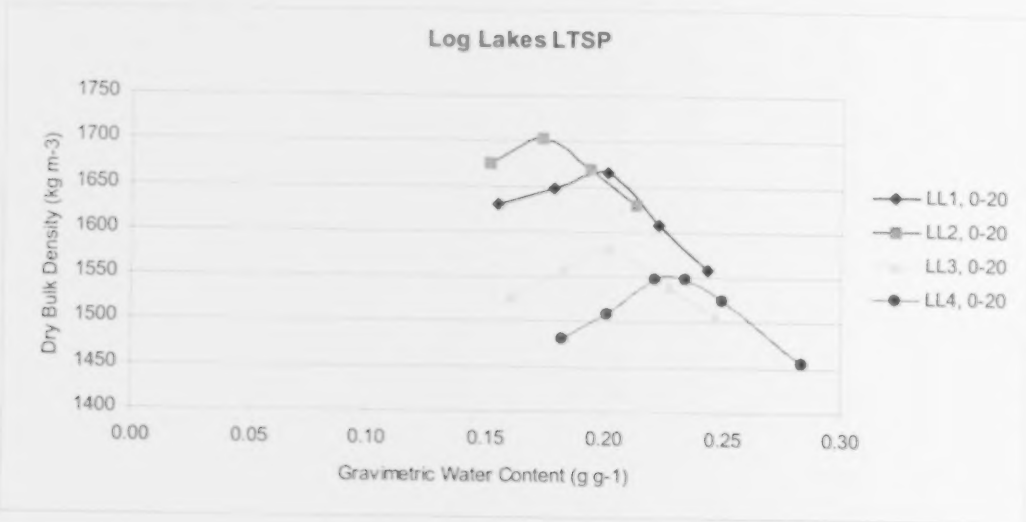
KO30, 10-20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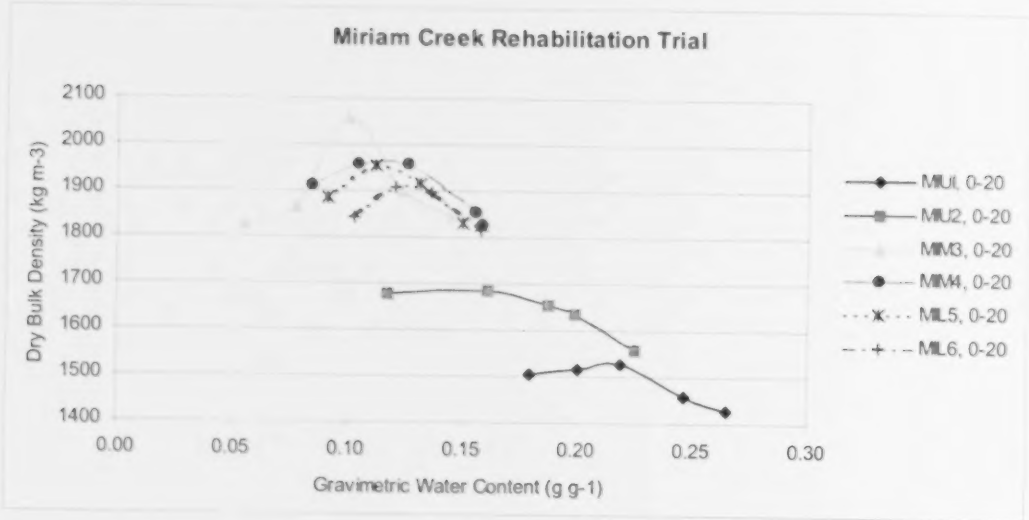
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1900
1800
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1600
1500
1400
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0.20
0.25
0.30
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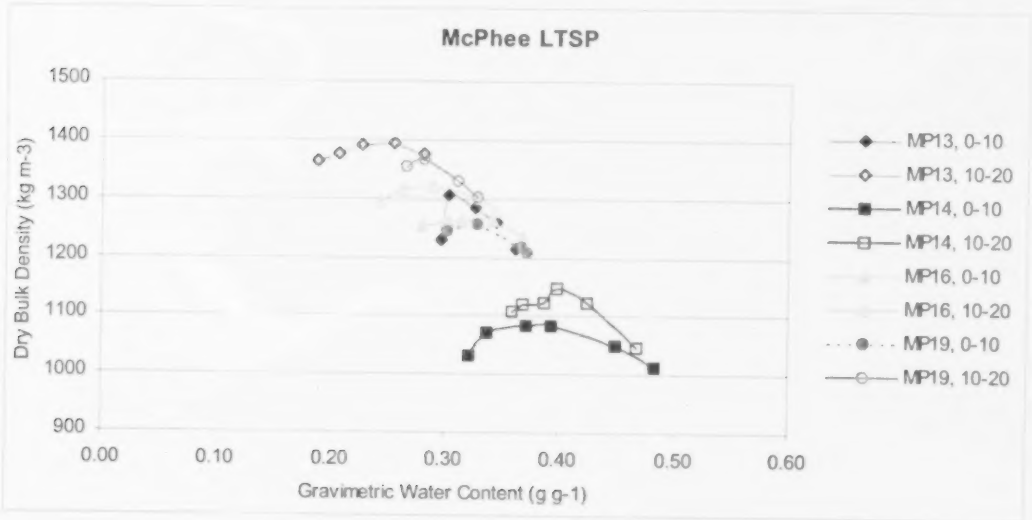
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0.50
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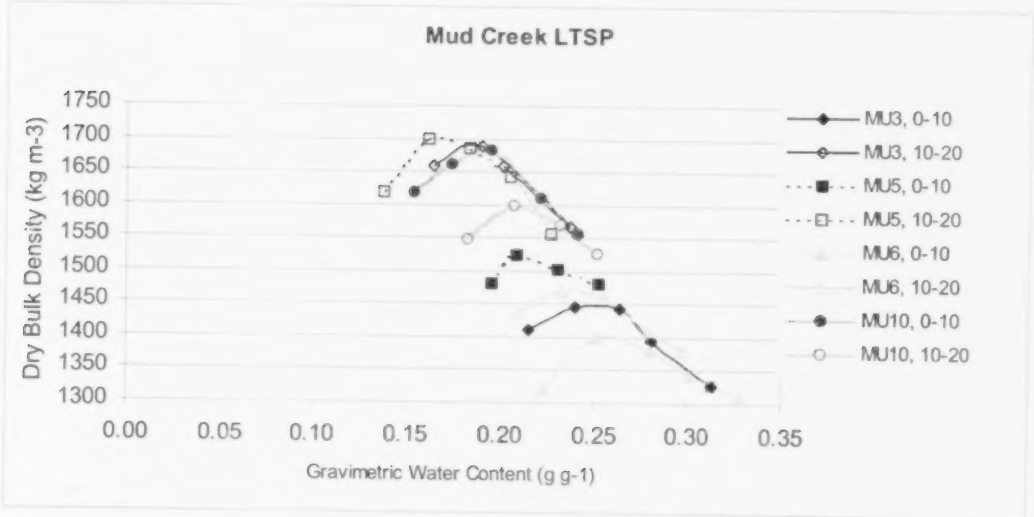
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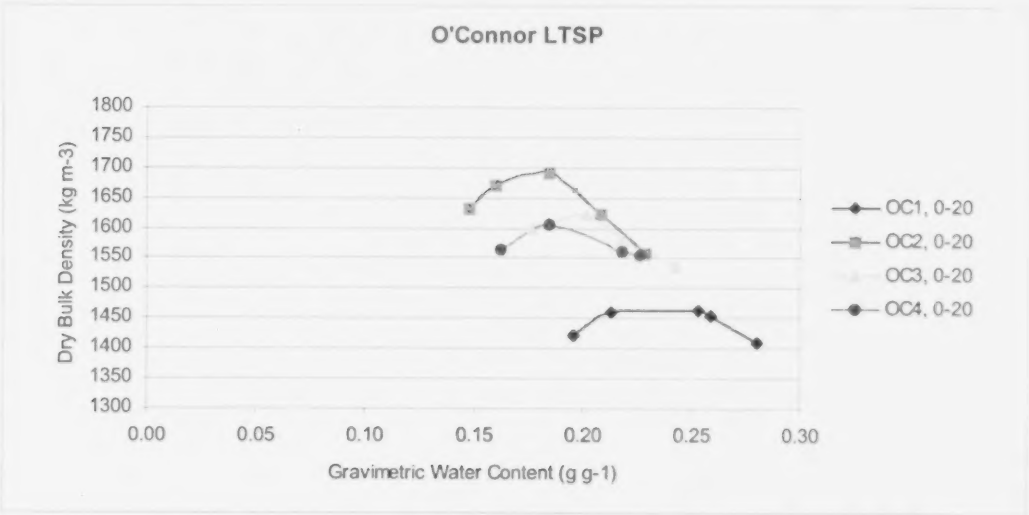
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1300
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0.05
0.10
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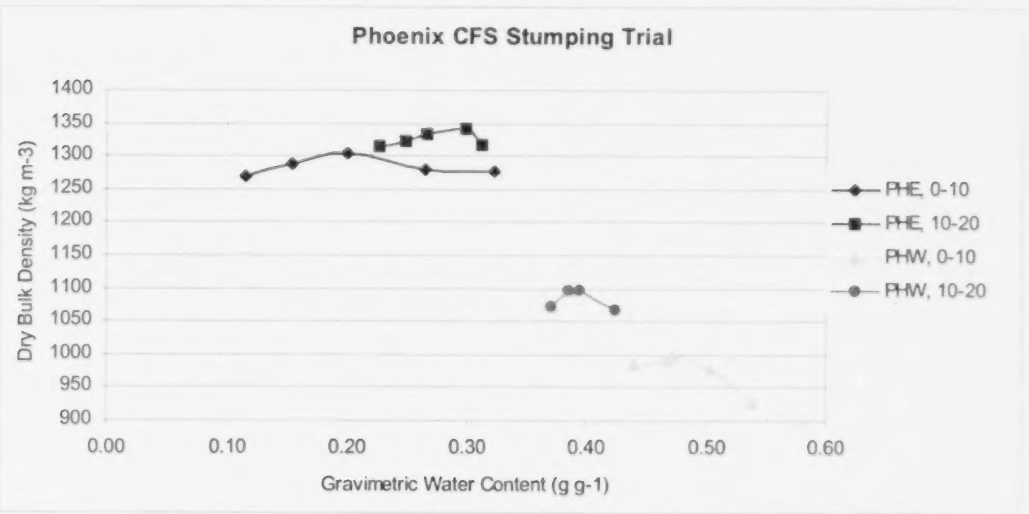
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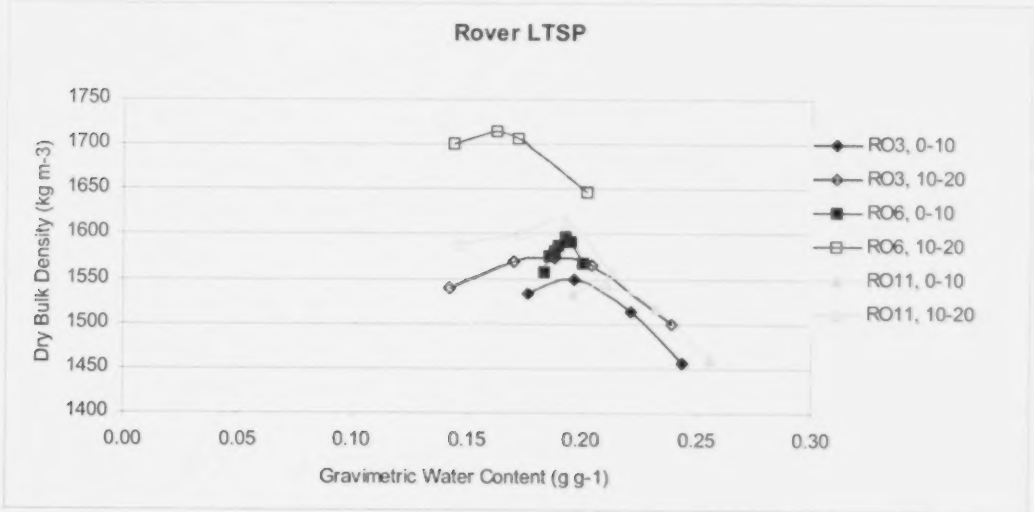
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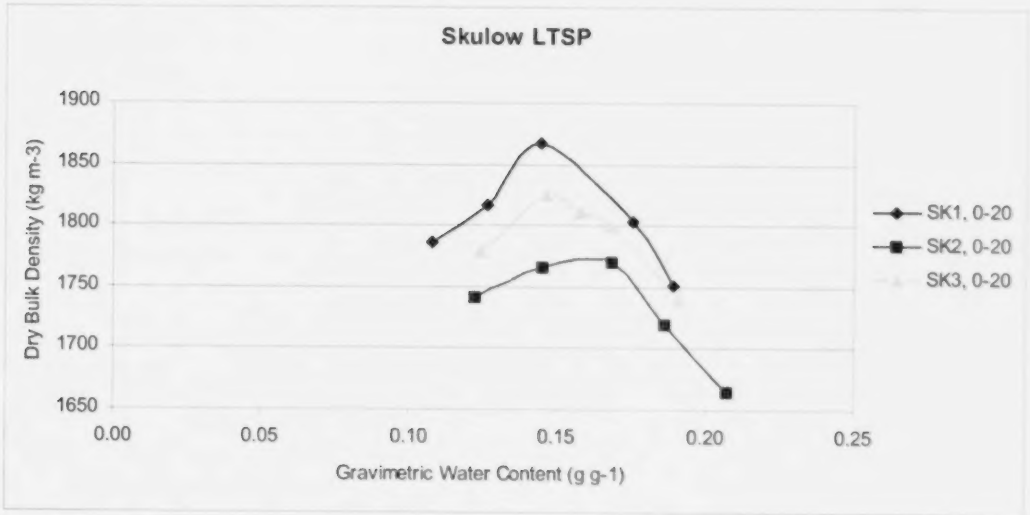
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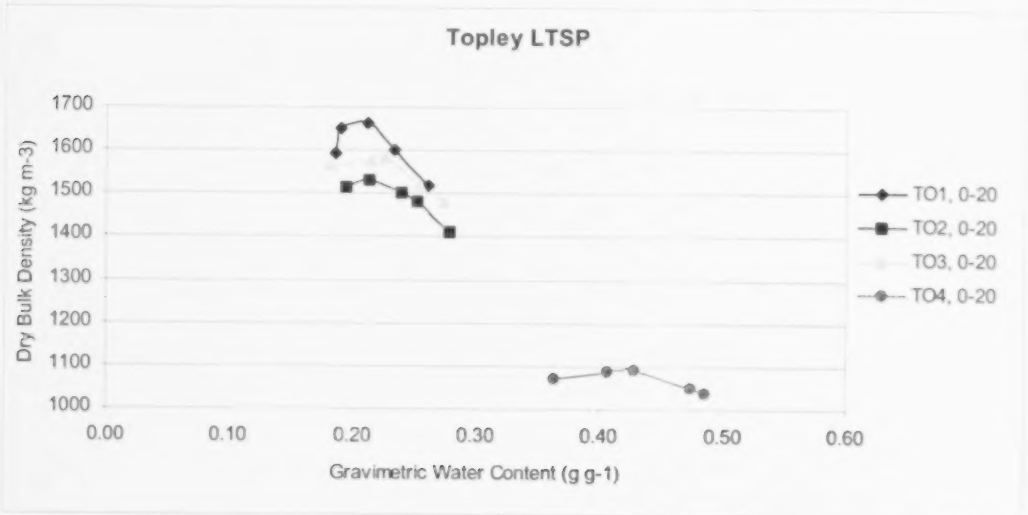
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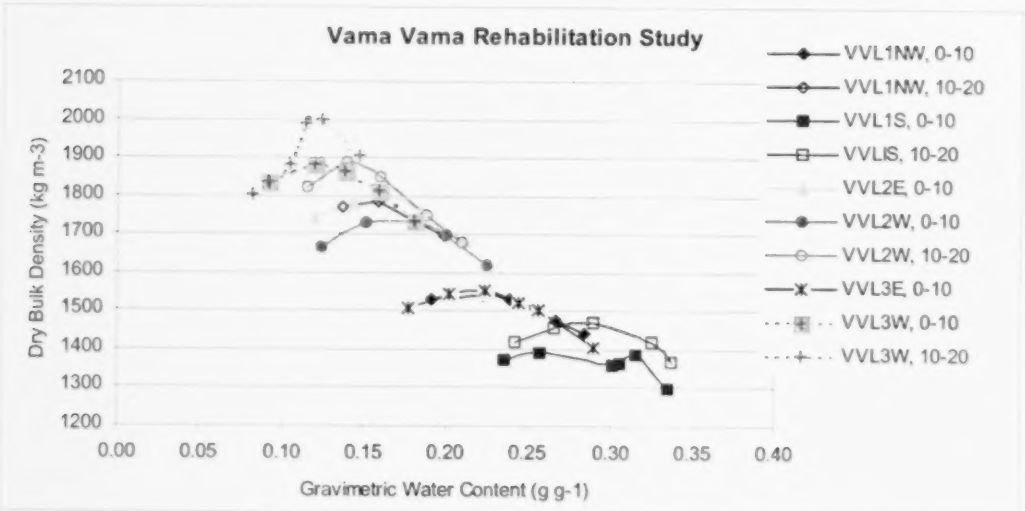
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0.10
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0.30
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VVL2E, 0-10
VVL2W, 0-10
VVL2W, 10-20
VVL3E, 0-10
VVL3W, 0-10
VVL3W, 10-20

Appendix B

Table 2: Site characterizations and Proctor test results for LTSP sites

Site ID and Depth (m)			Texture: Sand (100kg/kg)	Silt (100kg/kg)	Clay (100kg/kg)	Classification	Total Carbon (%)	Max Db ($Mg\ m^{-3}$)	Water Content at Max Db ($g\ g^{-1}$)
BP	1	0-0.2	38.37	51.34	10.29	Silt Loam	1.620	1.466	0.229
BP	2	0-0.2	33.37	53.48	13.15	Silt Loam	1.990	1.438	0.227
BP	3	0-0.2	37.51	47.91	14.58	Loam	2.080	1.441	0.229
BP	4	0-0.2	42.31	47.69	10.01	Loam	1.190	1.628	0.160
DA	1	0-0.2	33.51	58.34	8.15	Silt Loam	2.200	1.319	0.292
DA	2	0-0.2	33.01	55.34	11.65	Silt Loam	1.580	1.421	0.215
DA	3	0-0.2	46.18	45.73	8.09	Loam	1.180	1.717	0.140
DA	4	0-0.2	42.91	41.46	15.63	Loam	1.740	1.479	0.245
DW	A	0-0.1	26.05	52.07	21.88	Silt Loam	3.540	1.362	0.271
DW	A	0.1-0.2	31.85	55.60	12.55	Silt Loam	1.390	1.618	0.197
DW	B	0-0.1	21.93	54.64	23.43	Silt Loam	2.990	1.456	0.213
DW	B	0.1-0.2	23.30	60.50	16.20	Silt Loam	0.981	1.719	0.158
DW	C	0-0.1	15.67	70.10	14.23	Silt Loam	3.520	1.426	0.250
DW	C	0.1-0.2	15.44	75.46	9.10	Silt Loam	0.844	1.641	0.180
DW	D	0-0.1	33.70	43.77	22.53	Loam	5.530	1.234	0.331
DW	D	0.1-0.2	20.75	58.69	20.57	Silt Loam	1.520	1.578	0.201
DW	E	0-0.1	23.35	66.51	10.14	Silt Loam	1.680	1.588	0.194
DW	E	0.1-0.2	25.86	65.09	9.04	Silt Loam	0.431	1.723	0.164
DW	F	0-0.1	26.44	58.91	14.65	Silt Loam	3.720	1.361	0.278
DW	F	0.1-0.2	19.57	69.84	10.59	Silt Loam	0.632	1.710	0.158
EM	13	0-0.1	56.11	36.90	6.99	Sandy Loam	1.500	1.416	0.254
EM	13	0.1-0.2	68.95	25.97	5.07	Sandy Loam	0.518	1.702	0.085
EM	17	0-0.1	49.24	45.37	5.39	Sandy Loam	2.160	1.350	0.271
EM	17	0.1-0.2	73.51	23.99	2.49	Loamy Sand	0.935	1.619	0.151
KO	25	0-0.1	27.64	52.36	19.99	Silt Loam	2.760	1.361	0.268
KO	25	0.1-0.2	32.67	42.45	24.87	Loam	3.810	1.386	0.244
KO	26	0-0.1	30.11	49.51	20.38	Loam	5.060	1.118	0.343
KO	26	0.1-0.2	34.43	45.56	20.02	Loam	4.510	1.325	0.236
KO	27	0-0.1	24.45	56.28	19.27	Silt Loam	1.170	1.469	0.220
KO	27	0.1-0.2	23.72	52.03	24.25	Silt Loam	1.000	1.606	0.179
KO	30	0-0.1	24.27	54.92	20.81	Silt Loam	2.220	1.415	0.233
KO	30	0.1-0.2	30.14	45.84	24.02	Loam	3.480	1.431	0.220
LL	1	0-0.2	46.07	38.97	14.97	Loam	1.420	1.586	0.201
LL	2	0-0.2	48.29	42.12	9.59	Loam	0.933	1.610	0.173
LL	3	0-0.2	43.55	39.20	17.25	Loam	2.540	1.510	0.201
LL	4	0-0.2	37.08	41.13	21.79	Loam	1.730	1.494	0.221
MP	13	0-0.1	50.43	43.94	5.62	Sandy Loam	2.830	1.277	0.303
MP	13	0.1-0.2	46.11	50.85	3.04	Silt Loam	2.350	1.370	0.240
MP	14	0-0.1	34.20	59.57	6.23	Silt Loam	4.020	1.070	0.393
MP	14	0.1-0.2	31.10	60.80	8.09	Silt Loam	2.695	1.135	0.398
MP	16	0-0.1	41.79	53.37	4.84	Silt Loam	2.930	1.232	0.310
MP	16	0.1-0.2	42.03	53.95	4.02	Silt Loam	1.880	1.289	0.285
MP	19	0-0.1	36.40	56.98	6.62	Silt Loam	2.700	1.219	0.328
MP	19	0.1-0.2	38.07	56.40	5.53	Silt Loam	1.890	1.295	0.290

Table 2 (contd): Site characterizations and Proctor test results for LTSP sites

Site ID and Depth (m)			Texture: Sand (100kg/kg)	Silt (100kg/kg)	Clay (100kg/kg)	Classification	Total Carbon (%)	Max Db (Mg m-3)	Water Content at Max Db (g g-1)
MU	3	0-0.1	26.61	57.13	16.26	Silt Loam	1.820	1.420	0.241
MU	3	0.1-0.2	31.15	48.30	20.54	Loam	1.270	1.638	0.180
MU	5	0-0.1	27.85	54.66	17.49	Silt Loam	2.210	1.514	0.209
MU	5	0.1-0.2	27.17	44.24	28.59	Clay Loam	1.170	1.661	0.161
MU	6	0-0.1	22.18	60.43	17.38	Silt Loam	1.760	1.391	0.251
MU	6	0.1-0.2	20.27	58.32	21.42	Silt Loam	0.997	1.470	0.232
MU	10	0-0.1	32.34	42.65	25.01	Loam	5.240	1.622	0.194
MU	10	0.1-0.2	32.53	46.62	20.84	Loam	4.760	1.560	0.207
OC	1	0-0.2	40.70	48.19	11.11	Loam	2.570	1.418	0.232
OC	2	0-0.2	27.38	54.60	18.00	Silt Loam	1.380	1.631	0.175
OC	3	0-0.2	35.12	50.69	14.19	Silt Loam	1.340	1.577	0.202
OC	4	0-0.2	32.11	50.38	17.51	Silt Loam	1.440	1.548	0.185
RO	3	0-0.1	84.76	13.27	1.97	Loamy Sand	1.400	1.545	0.197
RO	3	0.1-0.2	85.44	8.61	5.95	Loamy Sand	1.100	1.570	0.188
RO	6	0-0.1	78.12	16.37	5.51	Loamy Sand	1.350	1.574	0.193
RO	6	0.1-0.2	86.73	10.75	2.52	Sand	0.748	1.687	0.163
RO	11	0-0.1	85.76	11.74	2.49	Loamy Sand	1.060	1.536	0.211
RO	11	0.1-0.2	85.33	8.85	5.82	Loamy Sand	0.881	1.604	0.186
SK	1	0-0.2	57.52	28.48	14.00	Sandy Loam	0.858	1.762	0.145
SK	2	0-0.2	55.42	37.52	7.06	Sandy Loam	0.971	1.702	0.160
SK	3	0-0.2	54.01	39.14	6.85	Sandy Loam	0.728	1.726	0.146
TO	1	0-0.2	60.03	26.97	13.00	Sandy Loam	2.265	1.503	0.205
TO	2	0-0.2	54.34	26.53	19.13	Sandy Loam	2.920	1.436	0.214
TO	3	0-0.2	50.23	27.33	22.44	Sandy Clay Loam	3.100	1.487	0.227
TO	4	0-0.2	42.86	29.63	27.51	Clay Loam	7.580	1.013	0.429

Table 3: Site characterizations and Proctor test results for non-LTSP sites
(Gates Creek Stumping Trial, Miriam Creek Rehabilitation Trial, Phoenix Canadian Forest Service Stumping Trial, Vama Vama Rehabilitation Study)

Site ID and Depth (m)			Texture: Sand (100kg/kg)	Silt (100kg/kg)	Clay (100kg/kg)	Classification	Total Carbon (%)	Max Db (Mg m^{-3})	Water Content at Max Db (g g^{-1})
GT	1	0-0.1	51.60	34.41	14.00	Loam	5.640	1.242	0.293
GT	1	0.1-0.2	48.92	36.36	14.72	Loam	5.900	1.147	0.315
GT	2	0-0.1	46.74	32.95	20.32	Loam	3.190	1.394	0.251
GT	2	0.1-0.2	48.40	34.04	17.55	Loam	1.450	1.503	0.186
MI	U1	0-0.2	62.12	32.44	5.44	Sandy Loam	3.860	1.346	0.2189
MI	U2	0-0.2	57.15	33.76	9.09	Sandy Loam	3.120	1.548	0.143
MI	M3	0-0.2	49.22	42.81	7.97	Loam	0.653	1.965	0.1002
MI	M4	0-0.2	55.09	38.08	6.83	Sandy Loam	0.785	1.849	0.115
MI	L5	0-0.2	50.44	35.39	14.17	Loam	0.686	1.845	0.112
MI	L6	0-0.2	66.73	28.20	5.07	Sandy Loam	1.090	1.771	0.121
PH	E	0-0.1	41.05	53.67	5.28	Silt Loam	2.860	1.241	0.2
PH	E	0.1-0.2	35.66	57.15	7.19	Silt Loam	1.640	1.268	0.3
PH	W	0-0.1	39.19	48.33	12.48	Loam	6.330	0.906	0.4724
PH	W	0.1-0.2	33.49	52.46	14.06	Silt Loam	5.890	0.996	0.389
VV	1N	0-0.1	44.63	41.10	14.27	Loam	3.460	1.456	0.215
VV	1N	0.1-0.2	46.47	43.05	10.48	Loam	0.839	1.723	0.15
VV	1S	0-0.1	23.88	37.50	38.63	Loam	2.370	1.374	0.2576
VV	1S	0.1-0.2	12.26	35.23	52.51	Clay	1.180	1.452	0.289
VV	2E	0-0.1	37.59	46.41	16.00	Loam	1.380	1.727	0.162
VV	2W	0-0.1	33.98	48.50	17.51	Loam	1.480	1.686	0.167
VV	2W	0.1-0.2	25.98	52.98	21.04	Silt Loam	0.269	1.867	0.14
VV	3E	0-0.1	39.60	43.48	16.92	Loam	2.790	1.500	0.22
VV	3W	0-0.1	50.39	40.59	9.02	Loam	0.740	1.815	0.1202
VV	3W	0.1-0.2	46.05	40.84	13.11	Loam	0.177	1.958	0.12

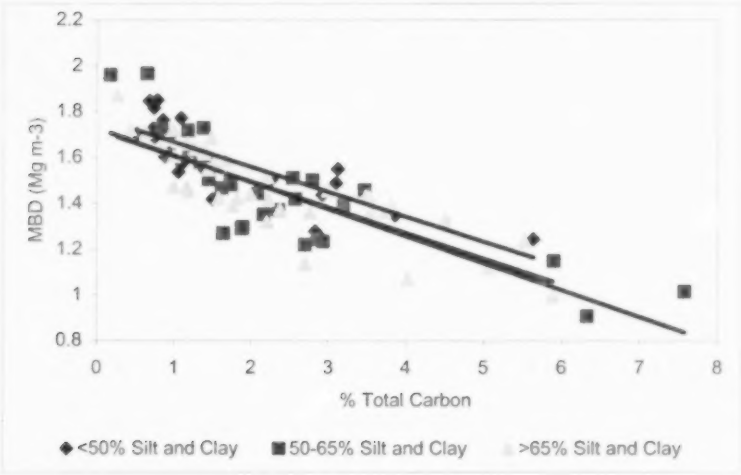

Figure 4: Relationship between total carbon sorted by silt and clay and maximum bulk density of 91 samples from 16 long term sites in BC

<50% Silt & Clay	y = -0.1084x + 1.7739	R^2 = 0.6652
50-65% Silt & Clay	y = -0.1176x + 1.7256	R^2 = 0.6531
>65% Silt & Clay	y = -0.112x + 1.7171	R^2 = 0.6967

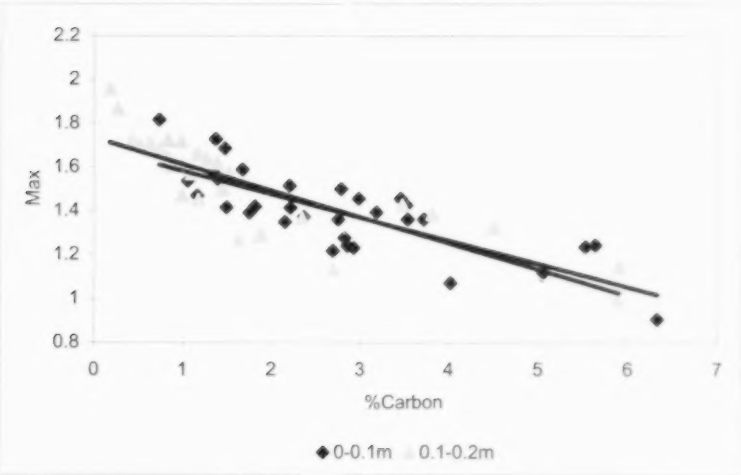

Figure 5: Relationship between total carbon sorted by depth and maximum bulk density of 91 samples from 16 long term sites in BC

0-0.1m	y = -0.1061x + 1.6884	R^2 = 0.6278
0.1-0.2m	y = -0.1201x + 1.7326	R^2 = 0.6697

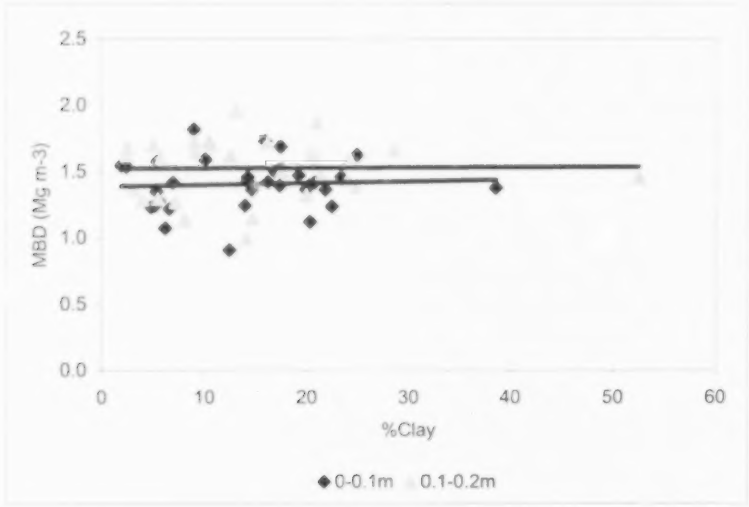

Figure 9: Relationship between clay content sorted by depth and maximum bulk density on 93 samples from 16 long term sites in BC

0-0.1m $y = 0.0013x + 1.3841$ $R^2 = 0.0031$
0.1-0.2m $y = 0.0003x + 1.5203$ $R^2 = 0.0002$

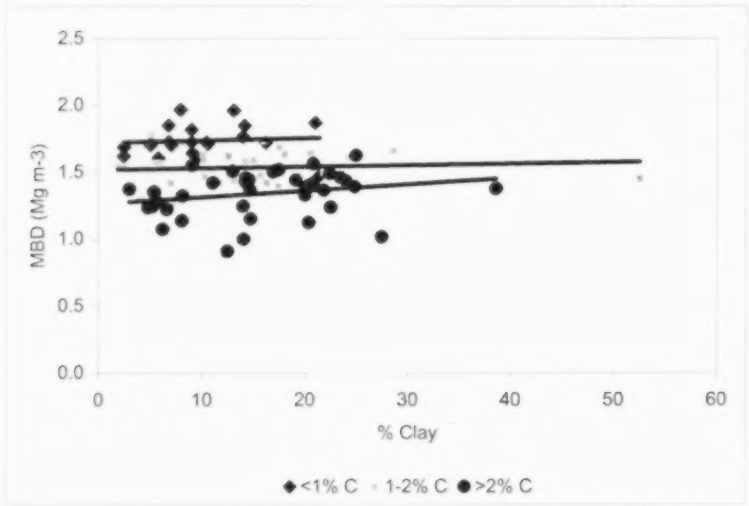

Figure 10: Relationship between clay content sorted by carbon and maximum bulk density on 93 samples from 16 long term sites in BC

<1% C $y = 0.0017x + 1.7179$ $R^2 = 0.0052$
1-2% C $y = 0.0011x + 1.5168$ $R^2 = 0.0073$
>2% C $y = 0.0048x + 1.2614$ $R^2 = 0.0513$

Appendix C

Table 6: Relative bulk density, field and Proctor carbon content, carbon differences against soil treatments at the Dawson Creek LTSP site

Treatment	RBD % 0-10 cm	RBD % 10-20cm	Field Carbon % 0-10 cm	Field Carbon % 10-20cm	Proctor Carbon % 0-10 cm	Proctor Carbon % 10-20cm	Carbon Difference % 0-10 cm	Carbon Difference % 10-20cm
OM1C0	59	94	1.48	0.72	1.68	0.63	-0.20	0.09
OM1C0	61	90	1.70	0.69	1.68	0.63	0.02	0.06
OM1C0	78	84	1.48	0.52	1.68	0.43	-0.20	0.09
OM2C0	66	72	4.36	1.95	1.68	1.52	2.68	0.43
OM2C0	75	82	1.71	0.58	1.68	0.63	0.03	-0.06
OM2C0	72	91	1.82	0.50	1.68	0.43	0.14	0.06
OM3C0	87	90	0.84	0.67	1.68	0.63	-0.84	0.04
OM3C0	80	87	1.42	0.66	1.68	0.63	-0.26	0.03
OM3C0	90	88	1.26	0.68	1.68	0.63	-0.42	0.05
OM1C1	68	86	1.44	0.58	1.68	0.63	-0.24	-0.05
OM1C1	70	92	1.72	0.66	1.68	0.63	0.04	0.03
OM1C1	82	93	1.30	0.85	1.68	0.84	-0.38	0.01
OM2C1	75	93	2.06	0.79	1.68	0.84	0.38	-0.06
OM2C1	84	91	1.53	1.01	1.68	0.98	-0.15	0.02
OM2C1	78	91	1.48	0.73	1.68	0.63	-0.20	0.09
OM3C1	91	92	0.94	0.63	1.68	0.63	-0.74	-0.01
OM3C1	96	88	1.07	0.52	1.68	0.43	-0.61	0.09
OM3C1	94	90	0.90	0.54	1.68	0.63	-0.79	-0.10
OM1C2	78	93	2.37	0.50	2.99	0.43	-0.62	0.07
OM1C2	64	91	1.62	0.63	1.68	0.63	-0.06	0.00
OM1C2	84	94	1.90	0.58	1.68	0.63	0.22	-0.05
OM2C2	75	86	2.24	0.73	2.99	0.63	-0.75	0.10
OM2C2	83	92	1.71	0.58	1.68	0.63	0.03	-0.05
OM2C2	89	94	2.49	0.62	2.99	0.63	-0.50	-0.01
OM3C2	91	91	0.78	0.50	1.68	0.43	-0.90	0.07
OM3C2	94	93	1.27	0.70	1.68	0.63	-0.42	0.06
OM3C2	90	88	1.37	0.83	1.68	0.84	-0.31	-0.02

Table 7: Relative bulk density, field and Proctor carbon content, carbon differences against soil treatmetns at the Log lake LTSP site

Treatment	RBD	Field Carbon	Proctor Carbon	Carbon Difference
	%	%	%	%
OM1C0	78	1.75	1.73	0.02
OM2C0	68	2.08	2.54	-0.47
OM3C0	77	1.64	1.73	-0.09
OM1C1	100	1.92	1.73	0.19
OM2C1	100	1.87	1.73	0.14
OM3C1	89	1.48	1.42	0.06
OM1C2	88	2.09	2.54	-0.45
OM2C2	80	2.04	2.54	-0.50
OM3C2	93	1.66	1.73	-0.08

Table 8: Relative bulk density, field and Proctor carbon content, carbon differences against soil treatments at the Topley LTSP site

Treatment	RBD	Field Carbon	Proctor Carbon	Carbon Difference
	%	%	%	%
OM1C0	102	2.18	2.27	-0.09
OM2C0	91	3.63	3.10	0.53
OM3C0	96	1.34	2.27	-0.93
OM1C1	101	1.48	2.27	-0.78
OM2C1	107	2.07	2.27	-0.19
OM3C1	98	1.97	2.27	-0.30
OM1C2	88	2.99	2.92	0.07
OM2C2	96	3.73	3.10	0.63
OM3C2	102	1.69	2.27	-0.57

Table 9: Relative bulk density, field and Proctor carbon content, carbon differences against soil treatments at the Skulow LTSP site

Treatment	RBD	Field Carbon	Proctor Carbon	Carbon Difference
	%	%	%	%
OM1C0	71	1.02	0.97	0.05
OM2C0	77	1.06	0.97	0.09
OM3C0	77	0.75	0.73	0.03
OM1C1	76	0.94	0.97	-0.03
OM2C1	80	1.00	0.97	0.02
OM3C1	80	0.89	0.86	0.04
OM1C2	85	1.00	0.97	0.03
OM2C2	80	1.03	0.97	0.06
OM3C2	86	0.64	0.73	-0.09

Table 10: Relative bulk density, field and Proctor carbon content, carbon differences against soil treatments at the Black Pine LTSP site

Treatment	RBD	Field Carbon	Proctor Carbon	Carbon Difference
	%	%	%	%
OM1C0	63	1.49	1.62	-0.13
OM2C0	71	2.00	2.08	-0.08
OM3C0	82	1.64	1.62	0.02
OM1C1	79	1.76	1.62	0.14
OM2C1	75	2.19	2.08	0.11
OM3C1	92	1.53	1.62	-0.09
OM1C2	79	2.24	2.08	0.16
OM2C2	85	1.86	1.99	-0.13
OM3C2	91	1.59	1.62	-0.03

Table 11: Relative bulk density, field and Proctor carbon content, carbon differences against soil treatments at the Dairy Creek LTSP site

Treatment	RBD	Field Carbon	Proctor Carbon	Carbon Difference
	%	%	%	%
OM1C0	64	2.21	2.20	0.01
OM2C0	68	2.65	2.20	0.45
OM3C0	60	1.71	1.74	-0.03
OM1C1	79	2.86	2.20	0.66
OM2C1	84	2.47	2.20	0.27
OM3C1	90	1.49	1.58	-0.10
OM1C2	79	2.50	2.20	0.30
OM2C2	92	2.48	2.20	0.28
OM3C2	94	1.90	2.20	-0.30

Table 12: Relative bulk density, field and Proctor carbon content, carbon differences against soil treatments at the O'connor LTSP site

Treatment	RBD	Field Carbon	Proctor Carbon	Carbon Difference
	%	%	%	%
OM1CO	61	2.69	2.57	0.12
OM2C0	61	2.95	2.57	0.38
OM3C0	74	1.50	1.44	0.06
OM1C1	72	2.86	2.57	0.29
OM2C1	76	2.01	2.57	-0.56
OM3C1	99	2.00	2.57	-0.57
OM1C2	76	2.11	2.57	-0.46
OM2C2	83	2.29	2.57	-0.28
OM3C2	74	1.63	1.44	0.19

Table 13: Relative bulk density, field and Proctor carbon content, carbon differences against soil treatments at the Vama Vama Rehabilitation Trial Site

Treatment	RBD %	RBD %	Field Carbon %	Field Carbon %	Proctor Carbon %	Proctor Carbon %	Carbon Difference %	Carbon Difference %
	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm
control1 (L1)	75	111	4.80	4.76	3.46	3.46	1.30	1.30
control1 (L2)	94	98	1.70	1.73	1.48	1.48	0.30	0.25
control1 (L3)	81	86	0.90	0.91	0.74	0.74	0.20	0.17
chptill (L1)	86	93	1.10	1.14	1.18	1.18	0.00	-0.04
chiptill (L2)	92	95	0.80	0.84	1.38	1.38	-0.50	-0.54
chiptill (L3)	77	85	1.30	1.28	0.74	0.74	0.50	0.54
sawtill (L1)	79	98	1.50	1.47	1.18	1.18	0.30	0.29
sawtill (L2)	75	81	0.50	0.47	0.27	0.27	0.20	0.20
sawtill (L3)	71	83	1.80	1.76	0.74	0.74	1.00	1.02
till (L1)	90	93	1.20	1.19	1.18	1.18	0.00	0.01
till (L2)	96	100	1.00	1.00	1.38	1.38	-0.40	-0.38
till (L3)	77	87	1.10	1.05	0.74	0.74	0.30	0.31

Table 14: Relative bulk density, field and Proctor carbon content, carbon differences against soil treatments at the Miriam Rehabilitation Trial Site

Treatment	RBD %	Field Carbon %	Proctor Carbon %	Carbon Difference %
shallow till	98	0.70	0.69	0.01
deep till	78	0.69	0.69	0.00
shallow till	92	0.98	1.09	-0.11
deep till	75	0.77	0.79	-0.01
shallow till	85	2.72	3.12	-0.40
deep till	72	3.77	3.12	0.65

Figure 17. Correlation between RBD and total of height lodgepole pine (Pl), Douglas-fir (Fd), White spruce (Sw), Hybrid spruce (Sx).

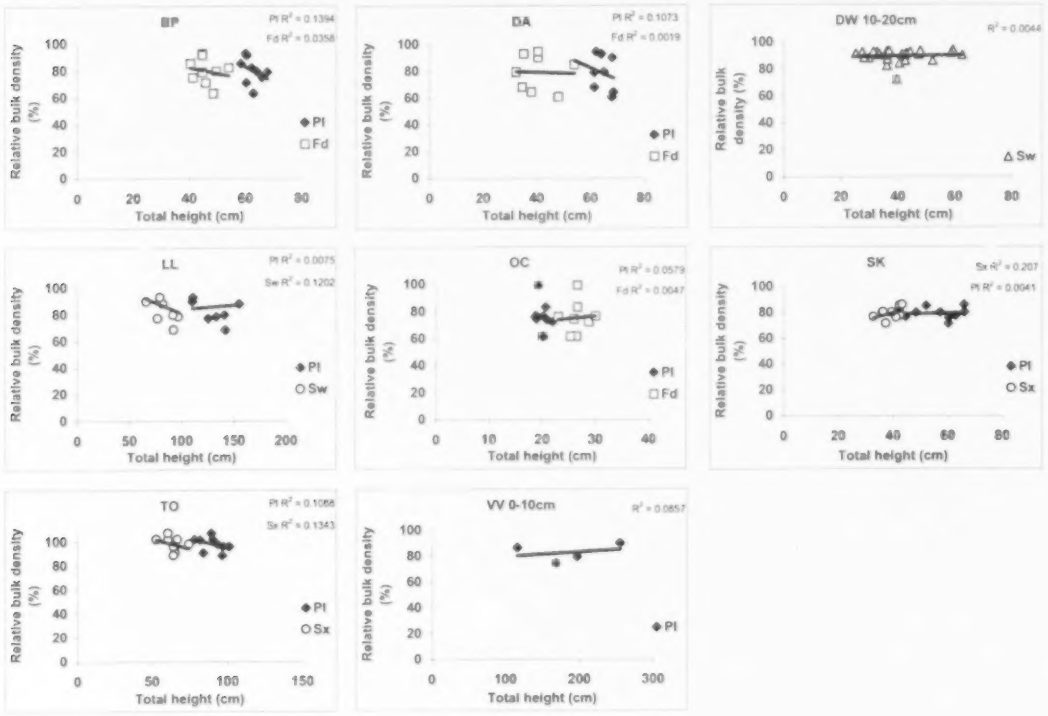

Figure 18. Correlation between RBD and height increment of lodgepole pine (Pl), Douglas-fir (Fd), White spruce (Sw), Hybrid spruce (Sx).